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Influence of baffle configurations on flow and heat transfer characteristics of trisection helical baffle heat exchangers

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ABSTRACT

Numerical simulation of flow and heat transfer characteristics in four trisection helical baffle heat exchangers with equilateral triangle tube layouts was conducted. The heat exchangers have the same helical pitch but four different baffle shapes or connections, i.e., a circumferential overlap (CO) scheme, an end-to-end (EE) scheme, a blocked V-notches (BV) scheme, and a middle axial overlap (MO) scheme. The single vortex secondary flow in each helical cycle and the leakage flow patterns in the V-notches of the adjacent baffles of these schemes are clearly depicted on the meridian slices and unfolded hexagon slices. The results for nine tubes in a 60° sector and four tube layers reveal that the local heat transfer coefficient of the center tube is much higher than that of the other tubes for all the schemes. The results show that the CO scheme has the highest shell-side heat transfer coefficient and comprehensive indexes, the BV scheme has the highest pressure drop and the worst comprehensive indexes, and the MO scheme has the lowest values of both shell-side heat transfer coefficient and pressure drop and the second highest comprehensive indexes. The average values of comprehensive index $h_o/\Delta p_o$ of CO scheme in the calculated range is respectively 16.5%, 27.3% and 13.5% higher than that of the EE, BV and MO schemes.

1. Introduction

The quadrant helical baffle heat exchangers proposed by Czech scientists Lutcha and Nemcansky [1] have many advantages, such as eliminating stagnant flow regions, decreasing shell-side pressure drop, and inhibiting tube bundle vibration damage and fouling, in contrast to segment baffle heat exchangers. Non-continuous helical baffles exhibit reverse leakage flows at the conjunction of adjacent baffles, which is a so-called leakage flow or shortcut in the triangular zone or V-notch between adjacent baffles and is generally believed to be one of major factors hindering heat exchanger performance.

Many improved methods pertaining to reverse leakage flow have been investigated experimentally or numerically. Stehlik et al. [2,3] suggested using axial overlap baffles to reduce the V-notch leakage and to shorten the support span of the baffles. Wang [4] measured the cold flow fields in helical baffle heat exchangers using laser Doppler anemometry to analyze the flow field velocity distribution for different overlap sizes. He et al. [5] and Zhang et al. [6] applied experimental investigation or numerical simulation to investigate a middle overlap quadrant helical baffle heat exchanger. All these papers in favor of this larger inclined angle but reduced spiral pitched axial overlap baffle scheme. Nevertheless, Nemati Taher et al. [7] numerically examined five helical baffle heat exchangers of 40° inclined angles with different baffle pitches and found the opposite conclusion that the comprehensive index of heat exchanger decreases with the increase in the axial overlap size. Lei et al. [8] studied a two-layer shell side scheme consists of inner and outer layer helical baffles with different incline angles and approximate spiral pitch to reduce the shortcut leakage between baffles, and the results showed that the comprehensive performance of the two-layer scheme is about 10% higher than that of the single-layer one. Wang et al. [9] tried to block the V-notches with plates but the results showed that it may lead to slight increase of the heat transfer coefficient with great penalty in pressure drop increase. There are some other schemes such as continuous baffle heat exchangers [10–12] and combined multiple shell-pass helical baffle heat exchangers [13–15] have been studied with different conclusions.

The quadrant helical baffle heat exchanger is suitable to a square tube layout. For the most popular equilateral triangle tube layout, trisection helical baffle configuration is a better choice in geometrical and symmetrical considerations. Chen et al. [16,17] proposed the trisection helical baffle heat exchanger configuration and constructed an anti-shortcut baffle structure called circumferential

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Nomenclature

A	heat transfer area based on the outer diameter of tube (m^2)
c_p	specific heat at constant fluid pressure ($J\ kg^{-1}\ K^{-1}$)
d_i	inner diameter of tube (m)
d_o	outer diameter of tube (m)
G_o	shell-side mass flow rate ($kg\ s^{-1}$)
h_o	shell-side heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
K	overall heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
k	turbulence kinetic energy ($m^2\ s^{-2}$)
Nu	Nusselt number
p	pressure (Pa)
P_p	shell-side pump power (kW)
Pr	Prandtl number
Q	heat transfer rate (kW)
Re	Reynolds number
S_Φ	generalized source term
T	temperature (K)
$\mathbf{U}$	velocity vector
u	velocity component in the x direction ($m\ s^{-1}$)
v	velocity component in the y direction ($m\ s^{-1}$)
w	velocity component in the z direction ($m\ s^{-1}$)

Greek symbols

Γ_Φ	generalized diffusion coefficient
Δp_o	shell-side pressure drop (kPa)
Δt_m	logarithmic mean temperature difference (K)
ε	turbulence kinetic energy dissipation rate ($m^2\ s^{-3}$)
ρ	density of fluid ($kg\ m^{-3}$)
ρ_o	density of shell-side fluid ($kg\ m^{-3}$)
η_p	pump efficiency
λ_i	thermal conductivity of tube-side fluid ($kW\ m^{-1}\ K^{-1}$)
λ_w	thermal conductivity of tube wall ($kW\ m^{-1}\ K^{-1}$)
Φ	universal variable

Subscripts

exp	experiment
i	tube side
o	shell side
sim	simulation
w	tube wall

overlap by widening the straight edges of the sector baffles to accommodate one or two rows of tubes in the circumferential overlap area of the adjacent baffles, and the experimental and numerical results indicated that the heat transfer performance was significantly improved. Dong et al. [18] experimentally studied several trisection helical baffle schemes and found that the performance of an axial overlap baffled scheme is worse than that of the end-to-end baffled scheme of either with identical inclined angled or with a smaller inclined angled but identical spiral pitch.

Experimental research is an indispensable step before a new type of heat exchanger is put into use; however, numerical simulation plays a crucial role in explaining how structural factors influence the flow and heat transfer of heat exchangers [19–27]. In this paper, four trisection helical baffle heat exchangers are compared. Numerical simulations were performed to explain how the baffle structural factors influence the flow and heat transfer of the following four helical baffle heat exchangers. The four heat exchanger schemes have approximately identical spiral pitch and tube geometry but different baffle shapes or connections, i.e., a circumferential overlap (CO) scheme, an end-to-end (EE) scheme, a blocked V-notches (BV) scheme and a middle axial overlap (MO) scheme.

2. Geometric model and numerical simulation

2.1. Geometric models

Four 3D geometric models and basic geometric parameters for the trisection helical baffle heat exchangers, as shown in Fig. 1 and Table 1, were established using the pre-processing software GAMBIT. The numerical simulation of heat transfer and pressure drop performances was conducted simultaneously for the shell side and the tube side. The physical models include the shell, tubes, tube plates, helical baffles, rods, and inlets and outlets for both sides, as shown in Fig. 1(a). The adjacent baffles of the EE scheme, BV scheme and the CO scheme all touch at the periphery of the sector baffles, and their incline angles are 20°, nevertheless, the adjacent baffles of the middle axial overlap scheme MO touch at the middle of the straight edges of the adjacent sector baffles, therefore its incline angle is 36.2° with identical pitch. All the four schemes are shown in Fig. 1(b)–(e), respectively.

2.2. Meshing

The post-processor software FLUENT is used to perform the simulation. Because FLUENT is more suitable for the unstructured grid, the geometric model of a trisection helical baffle heat exchanger is very complex, the discretization of the whole computational domain was performed with unstructured Tet-Hybrid elements of Tgrid type using GAMBIT. The grids adjacent to the tubes were refined to improve boundary layer calculation accuracy, as shown in Fig. 2. The grid independence tests were conducted with 2.1 M, 3.2 M, 3.9 M and 5.3 M grid programs. The computation of 2.1 M scheme was divergent, and the deviation of the Nusselt number Nu_o between the programs featuring grid numbers of 3.2 M and 3.9 M was more than 5% at the same shell-side mass flow G_o, and for 3.9 M and 5.3 M was within 2%. In consideration of the available computational capacity, the speed and accuracy, approximately 3.9 M grid cells were adopted for calculations for the four different heat exchanger schemes.

2.3. Governing equations

Fluid flow and heat transfer follow the three basic laws of conservation of mass, momentum and energy. The RNG k–ε turbulent viscosity model is used to provide improved flows with high streamline curvature for helical baffle heat exchangers. The mentioned equations can be described as a unified formula as follows:

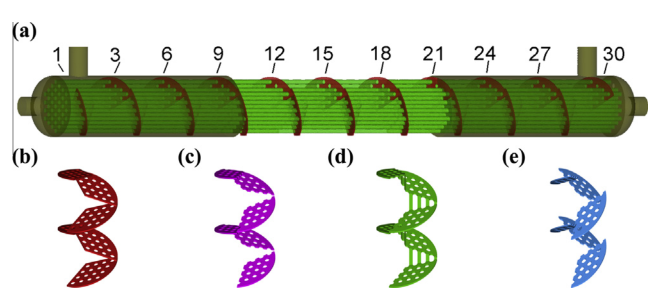

Fig. 1. Models of four trisection helical baffle heat exchangers: (a) assembly model of trisection helical baffle heat exchanger (number: ID of baffles); (b) circumferential overlap baffle (CO); (c) end-to-end baffle (EE); (d) blocked V-notches baffle (BV); (e) middle axial overlap baffle (MO).